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SCIENCE AND OPERATIONS CENTER

The NIRISS Wide-Field Slitless Spectroscopy Cookbook

An Informal Guide to Data Simulation and Analysis

Technical Report

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CM Foreword

This document is an STScI JWST Configuration Management-controlled document. Changes to this document require prior approval of the STScI JWST CCB. Proposed changes should be submitted to the JWST Office of Configuration Management.

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1 Introduction

1.1 The Software

The purpose of this document is to provide a brief introduction to the software available to model wide-field slitless spectroscopic observations with NIRISS and to extract and calibrate the resulting spectra. The tools employed are the aXe package of programs (Kümmel et al. 2009), which was developed to support slitless spectroscopy with ACS and WFC3 on the *Hubble Space Telescope*, and Source Extractor (a.k.a. SExtractor; Bertin & Arnouts 1996), which builds a catalog of objects from an astronomical image.

The aXe package includes three tools: aXeSIM is used to generate synthetic direct and dispersed images of the sky, aXe extracts and calibrates spectra, and aXe2web displays the resulting data in a convenient HTML format. (The web-based tool aXeSIMweb is not discussed in this document, as it currently simulates only WFC3 data.)

This cookbook follows closely the format of *The WFC3 IR Grism Data Reduction Cookbook*, version 1.15 (Kuntschner et al. 2012). Other useful documents are *The aXeSIM Manual*, version 1.4 (Kümmel, Walsh, & Kuntschner 2010) and the *aXe User Manual*, version 2.3 (Kümmel et al. 2011). Source Extractor is described in the *SExtractor User's Manual*, version 2.13 (Bertin 2009), and *Source Extractor for Dummies* (Holwerda 2005). All of these documents are included in the compressed tar file discussed in Section 2. Note that the WFC3 cookbook is subject to frequent revision. The most recent version is available from the [WFC3 Spectroscopy Resource Page](#).

1.2 The Instrument

The Near Infrared Imager and Slitless Spectrograph (NIRISS; Doyon et al. 2012) offers wide-field slitless spectroscopy (WFSS) with a resolving power $R = 150$ over the wavelength range 1.0 to 2.25 μm using either of two orthogonal gratings, GR150C and GR150R. The gratings are named such that GR150C disperses into detector columns (i.e., vertically) and GR150R disperses into rows (horizontally). If the gratings were used without a filter, their first-order spectra would overlap those of higher orders, and the sky background would be unacceptably high. Table 1-1 lists the five filters available for WFSS, their bandpasses, and the estimated count rates for zodiacal and stray light in each filter.¹

NIRISS employs a single HgCdTe detector with 2048×2048 pixels, each 18 μm across. The outer 4 pixels on each side are reference pixels, insensitive to light, so the active area is 2040×2040 pixels. The field of view is $134'' \times 135''$; each pixel thus spans 65.4 mas \times 65.8 mas. For simplicity, our models assume a plate scale of 64 mas/pixel.

For additional information about NIRISS, its capabilities, and modes of operation, see the NIRISS Operations Concept Document (Goudfrooij et al. 2012) and the NIRISS OSIM Test Plan (Martel 2012).

¹ See “A note about backgrounds” at the end of this section.

Table 1-1 Bandpass and Backgrounds for NIRISS Filters

Filter Name	Pivot Wavelength (nm)	Bandpass (μm)	Zodiacal Light ($\text{e}^-/\text{s}/\text{pix}$)	Stray Light ($\text{e}^-/\text{s}/\text{pix}$)
F090W	901	0.8 – 1.0	0.42	0.50
F115W	1150	1.0 – 1.3	0.43	0.47
F140M	1406	1.3 – 1.5	0.21	0.23
F150W	1498	1.3 – 1.7	0.44	0.48
F158M	1583	1.5 – 1.7	0.22	0.25
F200W	1984	1.75 – 2.25	0.39	0.44

Count rates represent the combination of a GR150 grism and the listed blocking filter.

A note about backgrounds: For sensitivity calculations, the *JWST* project uses a zodiacal-light spectrum scaled to 1.2 times its minimum intensity on the sky. Stray light refers to light from all objects (zodiacal dust, stars, Earth, and Moon) more than 1° from the line of sight that is scattered into the field of view by dust on the optics. Stray-light values are taken from Mission Requirement 121 (MR-121; Bussman 2011), which limits stray light to 0.091 and 0.070 MJy/sr at wavelengths of 2.0 and 3.0 μm , respectively. The dark current of the NIRISS detector adds an additional 0.015 e^-/s to each pixel. The read noise is roughly 6 e^-/pixel for a 1 ks exposure (assuming the standard NIRISS observing mode).

A note about F090W: At wavelengths between 0.8 and 0.9 μm , representing half of the F090W bandpass, the throughput of the GR150 grisms is higher in second order than in first.

1.3 What's New

The WFC3 cookbook begins with the reduction of an archival data set, then demonstrates the utility of aXeSIM in interpreting the resulting spectra. Lacking archival data for NIRISS, we begin by using aXeSIM to create a pair of direct and dispersed images (Sections 2 and 3), then use Source Extractor and aXe to identify the sources (Section 4) and extract their spectra (Section 5). We display the resulting spectra in an HTML format using aXe2web (Section 6). Because the aXe software can neither model nor extract spectra dispersed vertically on the detector, we provide instructions for simulating observations with grism GR150C (Section 7). We do not discuss the use of multidrizzle and axedrizzle to combine data from multiple exposures.

The aXe software package, along with our understanding of the NIRISS instrument and its operating modes, will evolve significantly in the years leading up to the launch of *JWST*. This document and the associated NIRISS configuration and calibration files will be revised as necessary to reflect these developments.

1.4 Reference Documents

[Bertin, E. 2009, SExtractor User's Manual, Version 2.13](#)

[Bertin, E. & Arnouts, S. 1996, Astronomy & Astrophysics Supplement, 317, 393](#)

Bussman, M. 2011, "JWST Mission Requirements Document," JWST-RQMT-000634, Rev. AD

Doyon, R., et al. 2012, in Space Telescopes and Instrumentation 2012: Optical, Infrared, and Millimeter Wave Conference, Proceedings of SPIE Vol. 8442

Goudfrooij, P., et al. 2012, “NIRISS Operations Concept Document,” in preparation

[Holwerda, B. W. 2005, Source Extractor for Dummies](#)

[Kuntschner, H., Kümmel, M., Walsh, J. R., & Lee, J. C. 2012, The WFC3 IR Grism Data Reduction Cookbook, Version 1.15](#)

[Kümmel, M., Walsh, J. R., & Kuntschner, H. 2010, The aXe SIMulation Package aXeSIM: User Manual, Version 1.4](#)

[Kümmel, M., Walsh, J. R., Kuntschner, H., & Bushouse, H. 2011, aXe User Manual, Version 2.3](#)

[Kümmel, M., Walsh, J. R., Pirzkal, N., Kuntschner, H., & Pasquali, A.J. 2009, PASP, 121, 59](#)

Martel, A. 2012, “OSIM Test Plan for ~~NIRISS~~ JWST- PL- 0012

2 Setting Up

2.1 Retrieve the Necessary Software and Configuration Files

Both aXe and aXeSIM are included in the PyRAF/IRAF package STSDAS. If this package is not available on your computer, the aXe software and its associated documentation can be retrieved from the [aXe website](#). The program aXe2web is not included in STSDAS, so must be installed by hand. (Here is a direct link to the [aXe distribution page](#).) The code and documentation for Source Extractor are available from [Astromatic.net](#).

The aXe programs require a number of calibration and configuration files, and they read and write files into a particular set of subdirectories. All are available as a single compressed tar file on the [NIRISS web site](#). Unpack this file in a convenient workspace. We will do all of our work within the resulting directory, called “cookbook.” Its subdirectories are

CONF	Configuration and calibration files
DATA	Input files used by aXe
DOCUMENTATION	User manuals
DRIZZLE	Required but not used by aXe
OUTPUT	Output files generated by aXe
OUTSIM	Output files generated by aXeSIM
SAVE	A safe copy of the input files used by aXe
SCRIPTS	Shell and Python scripts used by this cookbook
SIMDATA	Input files used by aXeSIM
VISUALIZATION	aXe2web works in this directory

2.2 Configure Your Environment

Define the following environment variables in the appropriate configuration file (.login, .mysetenv, .setenv, or equivalent):

```
# Environment Variables used by aXe
setenv AXE_CONFIG_PATH ./CONF
setenv AXE_DRIZZLE_PATH ./DRIZZLE
setenv AXE_IMAGE_PATH ./DATA
setenv AXE_OUTPUT_PATH ./OUTPUT
setenv AXE_OUTSIM_PATH ./OUTSIM
setenv AXE_SIMDATA_PATH ./SIMDATA
```

We have written a number of shell and Python scripts to save you some typing as you work through this cookbook. To use them, execute the following commands from within the cookbook directory:

```
> setenv PATH ${PWD}/SCRIPTS:${PATH}
> rehash
```

If you are working at STScI, follow the instructions at <http://stsdas.stsci.edu/configuration.html> to install and/or configure the latest version of STSDAS on your machine. Enter the command

```
> ssbrel
```

each time that you begin a session with this cookbook. Note that aXe2web (discussed in Section 6) is not installed on the STScI computers by default. You might want to go ahead and install it now.

3 Generate Synthetic Data

We begin by generating a pair of direct and dispersed images using aXeSIM. For this exercise, we consider only the F150W filter, but any of the other filters may be used.

3.1 Input Files Provided by the NIRISS Team

Both aXe and aXeSIM employ a suite of configuration and calibration files, most of which may be found in the CONF directory. A brief description of each file follows. Separate configuration, throughput, and sensitivity files are provided for each filter; the examples below are for F150W. Eventually, we will have a complete set of files for each grism; for the moment, we use one set of files for both.

`NIRISS.F150W.conf` – The configuration file, in ASCII format, describes the offset of each spectral order from the source in the direct image, the shape of the trace (i.e., the variation in Y as a function of X), and the dispersion solution of each order. All of these parameters may vary across the field of view. Once NIRISS is launched, we will measure them for each combination of grism and filter. For now, we model the position of each order, assuming that the offset is independent of detector position, the trace is constant in Y, and the dispersion is linear. The file also lists various instrument parameters, including the detector gain and read noise. The entry for the gain is commented out as a reminder that the aXe package works with images in units of e^-/s .

`NIRISS.F150W.tpass.V0.fits` – The throughput files are used to construct direct images of the field. They are FITS-format binary tables with two columns, wavelength and throughput. Wavelength is in Ångströms, and throughput is a real number between 0 and 1. The throughput multiplied by the area of the telescope yields the instrumental effective area at each wavelength, so the throughput includes everything from the shading by the secondary mirror to the detector quantum efficiency. Because this file is used only by aXeSIM, it lives not in the CONF directory but in SIMDATA.

`NIRISS.F150W.1st.sens.V0.fits` – The sensitivity files are used to construct spectra. The sensitivity is the product of the instrumental effective area (computed above) and the grism throughput, divided by the conversion from ergs to photons. The files are FITS-format binary tables with three columns: wavelength, sensitivity, and error. Wavelength is in Ångströms, and both sensitivity and error are in $e^-/s/\text{Å}$ per $\text{erg}/\text{cm}^2/\text{s}/\text{Å}$. (Section 6.1 of the aXe User Manual incorrectly states that the sensitivity is in e^-/s per $\text{erg}/\text{cm}^2/\text{s}/\text{Å}$.) At present, errors are simply 3% of the sensitivity. Separate files are provided for orders -1 through 3, for a total of five per filter. (In the example given here, “1st” refers to first order.)

`NIRISS.GR150R.flat.V0.fits` – This is *not* the flat-field file used in the standard JWST calibration pipeline. The response function of a detector is generally wavelength dependent. In slitless spectroscopy, a pixel can receive flux from any wavelength. Thus, aXe employs a wavelength-dependent flat-field correction. As we presently have no information about the flat field of the NIRISS detector, our flat field is simply a two-dimensional array of 1's. Note that aXeSIM ignores this file completely; any flat-field features must be added to the model images by hand.

`NIRISS.GR150R.sky.V0.fits` – When global subtraction of a master sky image is requested, aXe identifies uncontaminated regions on the detector, determines the mean level in

those regions, and scales the master sky image to match that mean. Once NIRISS is launched, we will construct a master sky image by combining grism images from multiple science programs, masking the object spectra in each. In the mean time, we assume that the background is uniform; our sky image is an array of 1's.

We won't actually feed the master sky image to aXeSIM. Instead, we will instruct the program to use a uniform background. Note that aXeSIM ignores dark current; any detector background must be included in the master sky image or added to the model images by hand.

3.2 Input Files Provided by the User

The aXeSIM Manual provides four examples of simulations with varying degrees of complexity. Here we provide a single example, but include a variety of input options.

3.2.1 Model Object Table

The model is controlled by the model object table (MOT), which describes the coordinates, magnitude, and shapes of all objects in the field. The MOT is an ASCII file in the form of a SExtractor output catalog; its format is fully detailed in Section 1.2 of *The aXeSIM Manual*. It lives in the DATA directory. Our MOT is called example.cat:

```
# 1  NUMBER          Object number
# 2  X_IMAGE         X coordinate (pixels)
# 3  Y_IMAGE         Y coordinate (pixels)
# 4  A_IMAGE         Length of semi-major axis (pixels)
# 5  B_IMAGE         Length of semi-minor axis (pixels)
# 6  THETA_IMAGE     Angle of major axis (counter-clockwise from +X axis)
# 7  MAG_F1537       Magnitude at 1537 nm (WFC3 F160W)
# 8  SPECTEMP        Key to spectral template
# 9  Z               Redshift
# 10 MODIMAGE        Key to model image
    1  900.00    700.00    0.5    0.5    0.0    22.5 0 0.0    0
    2  900.00    800.00    30.0   10.0   45.0   18.0 0 0.0    0
    3  900.00    950.00    18.0   10.0  -30.0   18.0 1 0.0    1
    4  900.00   1050.00     5.0    2.0   60.0   18.0 2 0.0    0
    5  900.00   1100.00     5.0    2.0   60.0   18.0 2 0.075 0
    6  900.00   1150.00     5.0    2.0   60.0   18.0 2 0.15   0
    7  900.00   1200.00     5.0    2.0   60.0   18.0 2 0.22   0
```

The object number (column 1) is not terribly important to aXeSIM, but central to the performance of aXe, as it is used to identify objects throughout the various stages of spectral extraction and calibration.

For each object in the MOT, the user may either supply a template image or describe its shape in terms of a 2-D Gaussian. If a template image is supplied, the object coordinates X_IMAGE and Y_IMAGE (columns 2 and 3) represent the point to which the center of the template is mapped. If a Gaussian is requested, they are the coordinates of the object centroid.

Columns 4, 5, and 6 list the object shape parameters. If a Gaussian is requested, then `A_IMAGE` is the length of its semi-major axis, `B_IMAGE` is the length of its semi-minor axis, and `THETA_IMAGE` is the angle between the major axis of the object and the X axis of the image, measured counter clockwise. (`A_IMAGE` and `B_IMAGE` describe the width of a 2-D Gaussian in the same way that σ does for a 1-D Gaussian.) These parameters should have reasonable values even if a template image is supplied, as they are used by aXeSIM to perform a toy extraction of the model spectrum.

Column 7 lists the total AB magnitude in one filter or at a particular wavelength. The column name indicates the pivot wavelength of the filter or the wavelength at which the magnitude was measured. In this case, `MAG_F1537` corresponds to a wavelength of 1537 nm, the pivot wavelength of the WFC3 F160W filter, through which (we will pretend) these galaxies have been observed. Any number of magnitudes may be specified. How they are used depends on whether a template spectrum is supplied.

If no template spectrum is supplied (the value in column 8 is 0), then a single magnitude value will result in an object spectrum that is constant in f_λ . Given two or more magnitudes, the program will interpolate linearly between them. At wavelengths beyond those of the listed magnitudes, the object spectrum is flat (*i.e.*, constant in f_λ).

If a template spectrum is supplied (the value in column 8 is greater than 0; see Section 3.2.2), it is first redshifted, then rescaled to match the magnitude given in the MOT. In the current example, object #3 has $mag_{AB} = 18.0$ at 1537 nm, which corresponds to a flux density of 3×10^{-17} erg/cm²/s/Å. The template spectrum will be averaged over the interval `tpass_flux` (specified on the command line) and rescaled to have a mean flux density of 3×10^{-17} erg/cm²/s/Å in that interval. The range of `tpass_flux` should match that of the magnitude given in the MOT. In our example, magnitudes were measured through the WFC3 F160W filter, which has a bandpass of 1400 to 1700 nm, so we set `tpass_flux = '1400,1700'`. If the wavelength of the input magnitude lies outside of `tpass_flux`, then the spectral scaling will probably be incorrect, but aXeSIM will not complain. If more than one magnitude is provided, the value closest to the pivot wavelength of `tpass_flux` is used. It is an error if the redshifted template spectrum does not span the wavelength interval `tpass_flux`.

This scaling algorithm can have a surprising effect: Two otherwise identical spectra will be scaled by wildly different factors if one has a strong emission feature within `tpass_flux` and the other does not.

If the requested redshift (column 9) is greater than zero, then the template spectrum is redshifted as described above. If the template spectrum is already redshifted, then you should set the value in the `REDSHIFT` column to zero. If no template spectrum is supplied, then the redshift is ignored.

If a template image is supplied (the value in column 10 is greater than 0; see Section 3.2.2), then the template image is centered on the point (`X_IMAGE`, `Y_IMAGE`) and dropped pixel-for-pixel onto the output image of the field. If `X_IMAGE` and `Y_IMAGE` are not integers, then the image is appropriately resampled. The user must apply any necessary convolution, shift, rotation, or spatial scaling of the template image before running aXeSIM. In particular, aXeSIM ignores all WCS information in the template-image header. If no template image is supplied (the

value in column 10 is 0), then a 2-D Gaussian described by the parameters A_IMAGE, B_IMAGE, and THETA_IMAGE is centered at the coordinates (X_IMAGE, Y_IMAGE).

Note that these columns may appear in any order, as long as they are properly labeled in the MOT header. Additional columns may be present, but they will be ignored by aXeSIM.

Now let us consider the seven objects in the MOT:

Object 1 is a star and thus unresolved. At 1.5 μm , the FWHM of the instrumental PSF is about 1.2 pixels, so we set both A_IMAGE and B_IMAGE = 0.5. The stellar magnitude is 22.5; the resulting spectrum will be flat in f_λ . We ignore the spectral and image templates by setting them to zero.

Object 2 uses a 2-D Gaussian to construct an image of an elliptical galaxy. The requested values of A_IMAGE, B_IMAGE, and THETA_IMAGE will produce an ellipse with a semi-major axis of 30 pixels, a semi-minor axis of 10 pixels, and a rotation angle of 45°.

Object 3 is a spiral galaxy. Here we employ both a template image (#1) and a template spectrum (#1). The template image has been convolved with the NIRISS PSF.

Finally, objects 4 through 9 are small galaxies, described with Gaussians, all using the same template spectrum (#2) but at a variety of redshifts. The spectrum is identical to that of object 3, but with a strong emission feature at 1.35 μm ; this line will march across the F150W bandpass as the redshift increases.

3.2.2 Template Spectra and Images

Both object spectra and images can be supplied via external files. Spectra may be either ASCII or binary FITS files containing two columns, the wavelength in Ångströms and the flux density in $\text{erg}/\text{cm}^2/\text{s}/\text{Å}$. The wavelength must increase monotonically. Images must be stored in FITS files with at most two extensions. If the file has two extensions, the first extension (i.e., the primary HDU) must be empty and the second must contain the data. The files are stored in the SIMDATA directory.

Lists of the template spectral and image files, here called template_spectra.txt and template_images.txt, are provided in the main directory. The names of these lists are provided to aXeSIM on the command line. The key used by the MOT to select a template from either list is simply the line number of the file in that list (beginning with line 1). If no template is desired, the key should be set to zero.

3.2.3 Scaling Spectra and Images

The spectrum of each object in the MOT is scaled according to the algorithm described in Section 3.2.1. To make the dispersed image, that spectrum is converted from physical units into e^-/s using the sensitivity files for each order. At each wavelength step, a copy of the object image is scaled to the appropriate intensity and dropped onto the output array. To make the direct image, the spectrum is scaled by the effective-area curve (the product of the telescope area and the throughput curve for the desired filter) and converted to units of e^-/s . A copy of the object image is then scaled and dropped onto the output array. Note that we have used input parameters (magnitudes and bandpass) for the WFC3 F160W filter, but output parameters (sensitivity and throughput curves) for the NIRISS F150W filter. The result is an (imaginary) image obtained through the NIRISS F150W filter.

3.3 Running aXeSIM

Once the input files are in place, aXeSIM can be run directly from the command line using the following python script:

```
> run_example.py
```

This script calls the program `simdata` with the following arguments:

```
simdata incat='example.cat' config='NIRISS.F150W.conf'  
tpass_direct='NIRISS.F150W.tpass.V0.fits' tpass_flux='1400,1700'  
inlist_spec='template_spectra.txt' inlist_ima='template_images.txt'  
bck_flux_dir = 0.94 bck_flux_disp = 0.94  
exptime_dir = 100 exptime_disp = 10000 extraction='YES'  
nx_disp=2040 ny_disp=2040 nx_dir=2040 ny_dir=2040
```

The parameters on the first three lines have already been discussed. In the fourth line, a uniform background is added to both the direct and dispersed images by setting the parameters `bck_flux_dir` and `bck_flux_disp` to $0.94 \text{ e}^-/\text{s}$, the sum of the zodiacal and scattered light through the F150W filter (Table 1-1) and the dark current for the NIRISS detector. Either a uniform background or a background image (in e^-/s) can be added using these parameters.

Exposure times for the direct and dispersed images are set by specifying the parameters `exptime_dir` and `exptime_disp`, respectively. aXeSIM scales the output image (sources plus background) to the requested exposure time, adds Poisson noise (for both sources and background) and read noise (from the configuration file), and divides by the exposure time to produce an image with units of e^-/s . While the EXPTIME keyword in the primary header will reflect the requested exposure time, the image itself will always be in units of e^-/s . If not provided with an exposure time, aXeSIM produces a noise-free image in units of e^-/s .

Note that the dispersed image has an exposure time of 10,000 seconds. In reality, such long exposures will be achieved by combining multiple shorter exposures. Current estimates suggest that, to minimize the data loss to cosmic rays, a single exposure should not exceed 1000 seconds in length (Robberto 2009).

Setting `extraction = yes` instructs the program to extract and calibrate spectra for each object in the field. The final four arguments insure that both the direct and dispersed images have 2040 pixels on a side; the default is 512.

3.4 aXeSIM Output

Six output files are written to the OUTSIM directory:

`example_direct.fits` – This is the direct image as it would look through the F150W filter. It is easily observed using a tool like SAOImage/DS9. Try using a logarithmic stretch. The seven targets are aligned vertically. The image has a background level of about $1 \text{ e}^-/\text{s}$ and Poisson noise, just as we requested.

`example_slitless.fits` – This is the dispersed image through the F150W filter. Again, it is best observed using a logarithmic scale. The X location of each target was chosen to place all five orders (-1 to 3) on the chip. The zero- and first-order spectra are reproduced in Figure 3-1. The top four galaxies clearly show the emission feature in each redshifted spectrum.

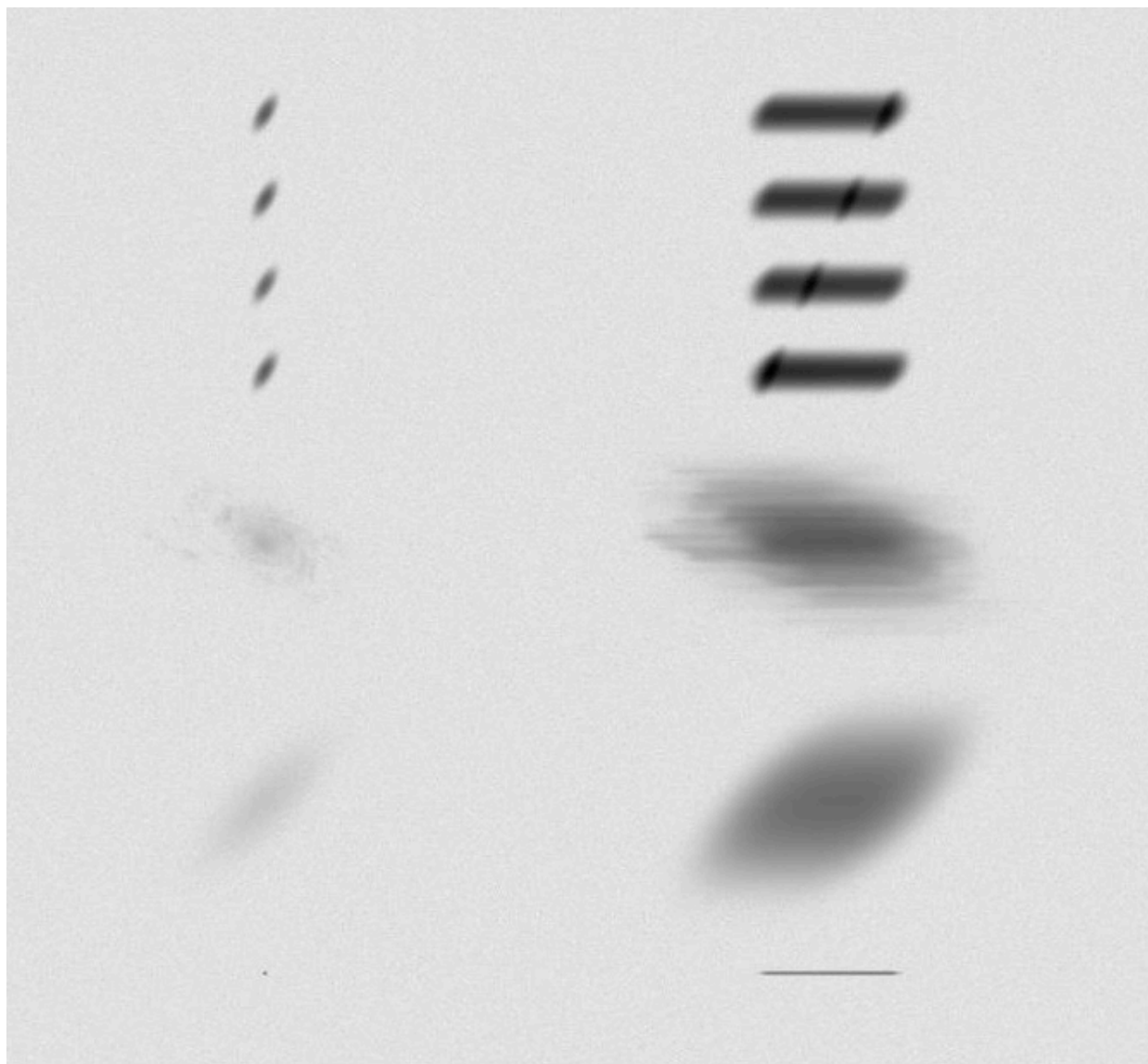


Figure 3-1 Zero- and first-order spectra of the seven objects in our example.

The first object (bottom of figure) is a star with a flat spectrum, the second a galaxy generated with a 2-D Gaussian, and the third a spiral galaxy using both a template image and a template spectrum. The last four galaxies have identical spectra with a single emission feature, but with increasing redshifts that move the emission feature across the bandpass.

Both the direct and dispersed images are normalized by the exposure time; that is, they have units of e^-/s . Both have the same toy file header with keywords appropriate for the ACS/HRC/G800L, the default if aXeSIM does not recognize your instrument. We will modify these keywords in Section 4.1.

`example_slitless_2.SPC.fits` – The SPC file contains the fully-calibrated, first-order spectrum of each object in the field. It is a multi-extension FITS file; each spectrum is stored in

a separate FITS binary table extension with two columns, wavelength and flux density. The file format is detailed in Section 4.9.1 of *The WFC3 Cookbook*. Note one cheat: aXeSIM performs its spectral extraction on a version of the dispersed image with no sky background, so the background subtraction is always perfect.

`example_slitless_2.STP.fits` – The STP file contains a two-dimensional image of each first-order spectrum. It, too, is a multi-extension FITS file; each spectrum is stored in a separate FITS image extension. The file format is detailed in Section 4.9.2 of *The WFC3 Cookbook*.

The SPC and STP files are standard output products of the aXe extraction routines. They were generated by aXeSIM because we set the parameter `extraction = yes`. Because these routines use the values of `A_IMAGE`, `B_IMAGE`, and `THETA_IMAGE` in the MOT, these parameters should have reasonable values, even if a template image of the object is provided.

`template_images.fits` – This is an intermediate data product. Each image in the template image list is normalized to an integrated intensity of 1.0 and stored in a separate FITS image extension. Even if multiple entries in the MOT use a particular image, only one copy is stored in this file.

`template_spectra.fits` – Another intermediate data product. Each spectrum in the template image list is redshifted to the requested value, scaled to the requested magnitude, and written to a separate FITS binary table extension. Because multiple entries in the MOT may use the same spectrum with different redshifts or scalings, each entry in the MOT that uses a template spectrum will generate a separate FITS binary extension.

Copies of `template_images.fits` and `template_spectra.fits` also appear in the DATA directory.

A couple of files are modified by aXeSIM. In the DATA directory, half a dozen additional columns are written to the MOT. These can be safely ignored, except for MODSPEC, which lists, for each target that employs a template spectrum, the extension in the file `template_spectra.fits` containing the redshifted and rescaled version of that spectrum. Note that aXeSIM rounds the redshift values to a single decimal place, changing (0.0, 0.075, 0.15, 0.22) to (0.0, 0.1, 0.1, 0.2).

In the CONF directory, a new copy of the configuration file has appeared with the suffix `.simul`. It is merely a reformatted version of the original.

A note about redshifts: We have seen that aXeSIM rounds the redshift values to a single decimal place in the modified version of the MOT. Figure 3-1 was generated using the script `run_example.py`. If instead IRAF/PYRAF is run interactively and `simdata` called from the command line (using the argument list in Section 3.3), aXeSIM will round the redshifts to a single decimal place *before* generating the dispersed image. Of the four galaxies at the top of the figure, the middle pair (objects 5 and 6) will have identical spectra with a redshift $z = 0.1$.

3.5 Reference Documents

[Kümmel, M., Walsh, J. R., Kuntschner, H., & Bushouse, H. 2011, aXe User Manual, Version 2.3](#)
[Kuntschner, H., Kümmel, M., Walsh, J. R., & Lee, J. C. 2012, The WFC3 IR Grism Data Reduction Cookbook, Version 1.15](#)

Robberto, M. 2009, “A Library of Simulated Cosmic Ray Events Impacting JWST HgCdTe Detectors,” JWST-STScI-001928

4 Prepare Input Files for Spectral Extraction

We move to the SAVE directory, where we will construct all of the input files required by aXe. Some of the aXe routines modify their input files, so we will leave copies here for safekeeping.

4.1 Copy and Modify Image Files

Both the direct and dispersed images produced by aXeSIM have header keywords appropriate for the ACS/HRC/G800L. We retrieve these images from the OUTSIM directory and modify their file headers. Finally, we copy the FITS image extension containing the direct image into a separate file.

```
> cd SAVE
> cp ../OUTSIM/example_direct.fits .
> cp ../OUTSIM/example_slitless.fits .
> modify_header.py example_direct.fits
> modify_header.py example_slitless.fits
> copy_extension.py example_direct.fits sci example_direct_sci.fits
```

All of the above steps have been combined into a single python script, which should be run from within the SAVE directory.

```
> run_modify_files
```

4.2 Use SExtractor to Construct New MOT

When wide-field slitless spectroscopy is performed using *HST*, a direct image is always obtained in the same visit as the dispersed image. A catalog derived from the direct image is used to identify spectra for extraction with aXe. Assuming that *JWST* will be used in the same way, we employ SExtractor to catalog the objects in our direct image.

SExtractor requires a pair of input files: a configuration file (example.sex) describing the data and a parameter file (example.param) listing the object parameters that the program should tabulate. The configuration file is described in Section 4.2 of the *SExtractor User's Manual*, while the list of parameters required by aXe is discussed in Section 7.2 of the *aXe User Manual*. You can see which values in the configuration file we have changed by comparing our version with the default:

```
> sex -d > default.sex
> diff default.sex example.sex
```

In particular, we have modified

DETECT_MINAREA	7	<i>Default value is 5</i>
DETECT_THRESH	3.0	<i>Default value is 1.5</i>
ANALYSIS_THRESH	3.0	<i>Default value is 1.5</i>
MAG_ZEROPOINT	28.1844	<i>Yields 1 e-/s through F150W</i>
GAIN	100.0	<i>Exposure time; used in calculating magnitude errors</i>
PIXEL_SCALE	0.064	<i>Size of pixel in arcsec</i>
SEEING_FWHM	0.08	<i>Stellar FWHM in arcsec</i>
CHECKIMAGE_TYPE	APERTURES	

CHECKIMAGE_NAME apertures.fits

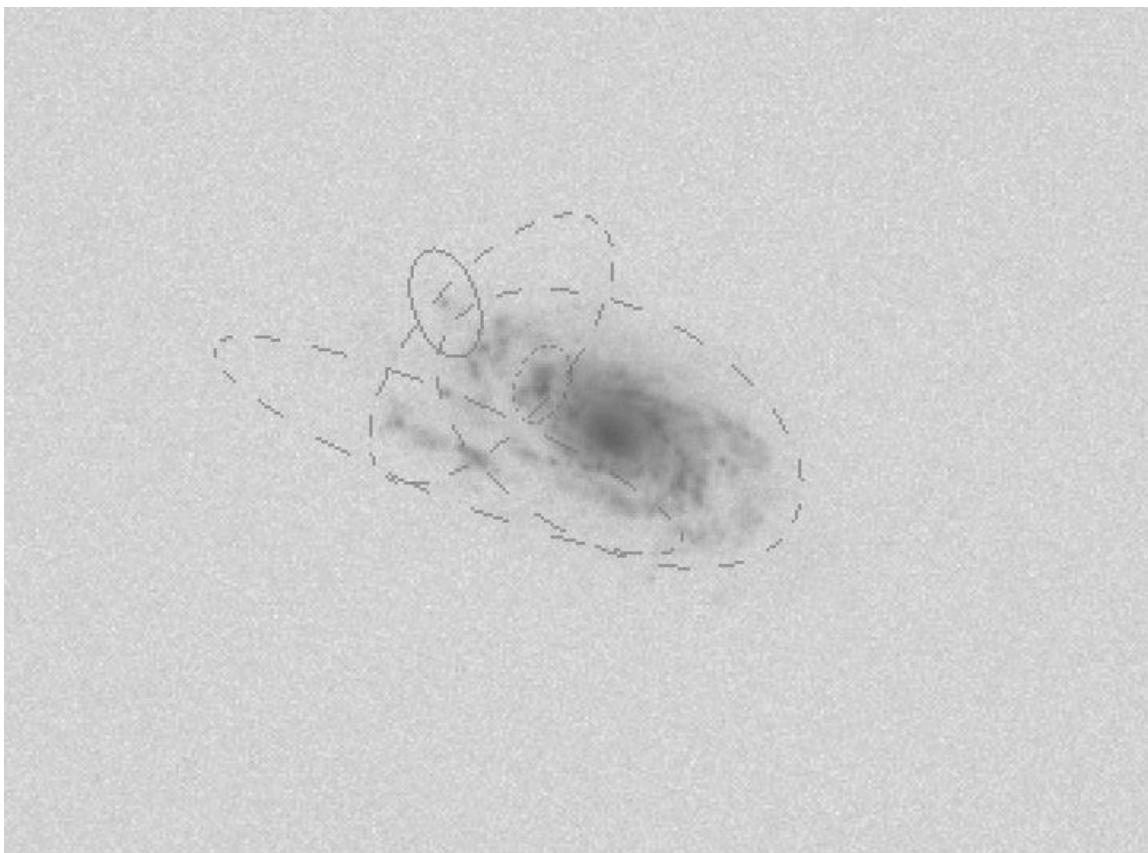


Figure 4-1 Detail of `apertures.fits` showing that SExtractor has identified our spiral galaxy as five separate objects.

Setting the CHECKIMAGE keyword to APERTURES will cause SExtractor to generate a copy of the input image with apertures drawn around the identified objects.

We have *not* changed FILTER_NAME, the kernel used to smooth the image before bright regions of the image are separated into different objects. We use the default kernel, default.conv, a pyramidal function with FWHM = 2. For this exercise, a more sophisticated kernel is unnecessary, but you might try playing with others later on. If you are not using a machine at STScI, you must edit FILTER_NAME, giving the full path to default.conv on your machine.

Now run SExtractor:

```
> sex -c example.sex example_direct_sci.fits
```

Output files are F150W.cat and apertures.fits. The catalog lists 11 (or more) objects, which is odd, because we created only seven. A quick perusal of the image in apertures.fits (reproduced in Figure 4-1) reveals that parts of our large spiral galaxy were identified as separate objects. Rather than play with the detection parameters in the SExtractor configuration file, you can simply delete the extra entries (those whose X coordinates differ from 900 by more than a couple of pixels) from the catalog.

While you are modifying the catalog, please change the magnitude header keyword from MAG_AUTO to MAG_F1498. One of the aXe routines will use the magnitude of each object to

compute its flux density, and it needs to know the wavelength at which the magnitude was measured. Another aXe routine will use these magnitudes to estimate the contamination from overlapping orders.

There may be other reasons to tinker with the output catalog. If SExtractor cannot estimate a magnitude for an object, then it assigns a magnitude of 99. This value will lead to an error in the aXe reduction software. Either replace the magnitude with a realistic number or remove the object from the catalog.

4.3 Construct Input Image List

aXe requires an Input Image List that links together the various input files. The format is [name of grism image] [object catalog] [name of direct image]

In our example, the file GR150R.lis contains the single line

```
example_slitless.fits F150W.cat example_direct.fits
```

4.4 Move Files into Position

We leave the files that we have just generated in the SAVE directory and place copies in the directories where aXe expects to find them:

```
> cp GR150R.lis ..
```

```
> cp example_direct.fits example_slitless.fits F150W.cat ../DATA
```

or simply run this script:

```
> run_copy_files
```

5 Extract Spectra from Dispersed Image

Before running aXe itself, please return to the main cookbook directory.

5.1 Preparing the Spectral Extraction: `axeprep`

This program subtracts the background from the dispersed image. It also creates a file listing, for each object in the catalog, the boundaries of each order and the flux therein. The fluxes will not be computed if the catalog contains the header keyword `MAG_AUTO`, so double-check that you have changed it to `MAG_F1498`. To run the program, enter

```
axeprep GR150R.lis NIRISS.F150W.conf backgr='yes'
        backims='NIRISS.GR150R.sky.V0.fits' norm='no'
```

or use our handy Python script:

```
> run_axeprep.py
```

5.2 Extracting Individual Spectra: `axecore`

Finally, we run aXe itself, but with command-line arguments slightly different from those employed by *The WFC3 Cookbook*:

```
axecore GR150R.lis NIRISS.F150W.conf extrfwhm=4.0 drzfwhm=3.0
back='no' backfwhm=0.0 orient='yes' slitless_geom='yes'
cont_model='gauss' sampling='drizzle' lambda_mark=1500
```

We have changed the parameters `orient` and `slitless_geom` to “yes.” These commands tell aXe to tilt the extraction window by the rotation angle `THETA_IMAGE` of the galaxy, thus improving the resolution of the extracted spectrum.

Again, we provide a Python script to save you some typing:

```
> run_axecore.py
```

The output files generated by aXe are thoroughly documented in Section 4.9 of *The WFC3 Cookbook*, and we will not repeat that discussion here. In addition, we direct your attention to the discussion of quality control in Section 5.1 of that document.

5.3 Reference Documents

[Kuntschner, H., Kümmel, M., Walsh, J. R., & Lee, J. C. 2012, The WFC3 IR Grism Data Reduction Cookbook, Version 1.15](#)

6 Creating Web Pages to Review Your Results

The creators of aXe have provided a handy tool for displaying the program’s output products. The program, aXe2web, constructs web pages showing the direct image, the two-dimensional spectrum, and the extracted spectrum in units of both e^-/s and $\text{erg}/\text{cm}^2/\text{s}/\text{\AA}$ for each object in the catalog. This tool is thoroughly documented in Section 5.2 of *The WFC3 Cookbook*, but we supplement that discussion with information specific to our NIRISS simulation. In particular, because we do not employ axedrizzle, we must use the output products of axecore directly.

- Step 1: Move to the visualization directory

```
> cd VISUALIZATION
```

- Step 2: Copy all of the necessary files into place.

```
> cp ../SAVE/example_direct_sci.fits .
```

```
> cp ../DATA/F150W.cat .
```

```
> cp ../OUTPUT/example_slitless_2.SPC.fits .
```

```
> cp ../OUTPUT/example_slitless_2.STP.fits .
```

or just use our script

```
> get_vis_files
```

- Step 3: Make a parameter file to control the program. Ours is GR150R.par:

```
#
```

```
# Example
```

```
#
```

```
pagename = GR150R
```

```
direct_image = example_direct_sci.fits
```

```
stamp_image = example_slitless_2.STP.fits
```

```
spectr_table = example_slitless_2.SPC.fits
```

```
sextract_cat = F150W.cat
```

```
sort_column = MAG_F1498
```

```
page_header = "aXe2web GR150R"
```

```
pagesize=50
```

```
errorBars=yes
```

```
mark_sources=yes
```

```
outputpath=web_pages
```

```
lambda_range=13000,17000
```

```
#
```

- Step 4: Run aXe2web with the parameter file.

```
> aXe2web --parfile GR150R.par
```

If your computer replies, “Command not found,” then you must install aXe2web, which is available from the [aXe distribution page](https://soccer.stsci.edu).

- Step 5: Review the output.

```
> open web_pages/GR150R.html
```

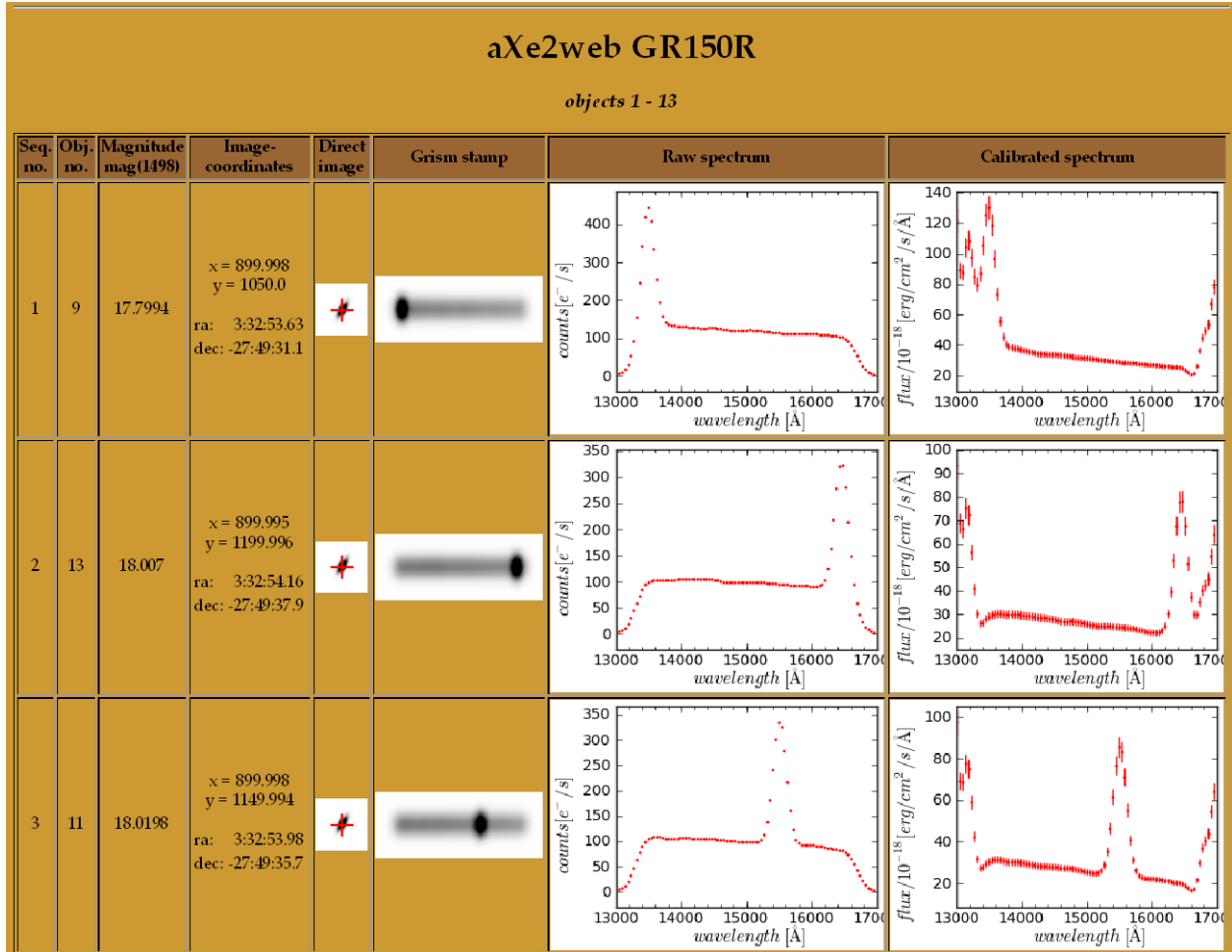



Figure 6-1 Output of aXe2web, showing the direct image, the two-dimensional spectrum, and the extracted spectrum in both counts and flux units for each object in the catalog.

As shown in Figure 6-1, objects are sorted by magnitude and retain the object number from the catalog. Our use of a tilted extraction window results in 2-D spectra in which the galaxies appear to be aligned perpendicular to the spectral trace, resulting in much narrower emission features than would otherwise be the case. If present, the blue line in the flux-calibrated spectral plots represents aXe's estimate of contamination due to background sources. It is zero for all of our objects, so does not appear in these plots.

The count-rate spectra drop to zero at the edges of the filter bandpass, but the flux-calibrated spectra rise sharply in the same regions. This discrepancy reflects a limitation in the sensitivity curves, which are derived from observations of point sources (or in our case, from simulations of point sources) but applied to extended objects. The effect can be reduced by setting the parameter `adj_sens='yes'` in the call to `axecore`, which instructs aXe to smooth the sensitivity function by convolving it with a Gaussian kernel scaled to the width of the object. See the discussion of flux conversion in Section 1.11 of the *aXe User Manual*.

6.1 Reference Documents

[Kümmel, M., Walsh, J. R., Kuntschner, H., & Bushouse, H. 2011, aXe User Manual, Version 2.3](#)
[Kuntschner, H., Kümmel, M., Walsh, J. R., & Lee, J. C. 2012, The WFC3 IR Grism Data Reduction Cookbook, Version 1.15](#)

7 Simulating Observations with GR150C

The configuration files used by the aXe programs describe the shape of the spectral trace, the limits of each order, and the wavelength solution using functions of the horizontal axis X. Because spectra dispersed vertically on the detector cannot be represented by such functions, aXe cannot properly extract and calibrate them. To model vertically-dispersed spectra, we will pretend that there is no grism GR150C and instead employ grism GR150R, combined with a telescope rotation of 90°. To this end, we will rotate our model sky clockwise, which is equivalent to rotating the telescope counter-clockwise.

7.1 Rotate the Catalog and Any Template Images

The following code fragment will rotate the input catalog by -90° (clockwise) about the center of the detector:

```
x_rot = y_image
y_rot = 2041. - x_image
theta_rot = theta_image - 90.
if theta_rot < -90.:
    theta_rot += 180.
```

This code is implemented in the Python script `rotate_catalog.py`. You can use it to rotate the input catalog in the DATA directory. Since `example.cat` was modified by aXeSIM, use the copy stored in `example.save`:

```
> cd DATA
> rotate_catalog.py example.save rotate.cat
```

Important: Suppose that your field is oriented with north on top. If you use horizontal dispersion, then the spectra of the galaxies in the field are contaminated by the spectra of galaxies that lie to the east and west of the field. If you use vertical dispersion, then the contamination comes from galaxies to the north and south. If your input catalog is too small, then your dispersed images will lack these overlapping spectra. Be sure that your input catalog covers a sufficient area of the sky to provide these sources of contamination.

Because aXeSIM ignores the value of THETA_IMAGE when working with template images, you must rotate each template image by hand. Here’s a little script to do that job:

```
> cd SIMDATA
> rotate_image.py spiral.fits spiral-90.fits
```

Be sure to modify the file `cookbook/template_images.txt` accordingly.

7.2 Rotate the Image Header

Now run aXeSIM as described in Section 3.3, but using the script `run_rotate.py` in place of `run_example.py`. The resulting direct and dispersed images will appear as though the telescope had been rotated by 90°. To complete the illusion, we must modify the World Coordinate System keywords in the file header. To do this, simply add the argument “rotate” to your call to `modify_header.py`, discussed in Section 4.1.

```
> modify_header.py rotate_direct.fits rotate
> modify_header.py rotate_slitless.fits rotate
```

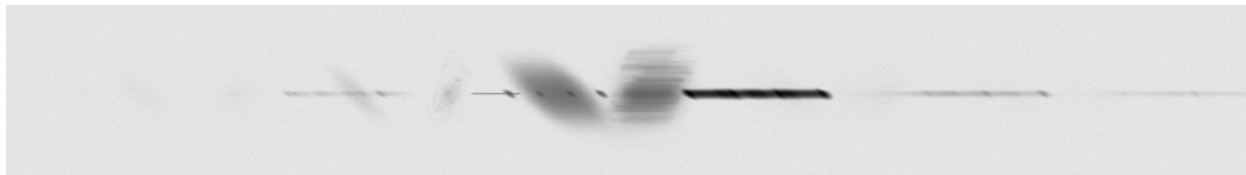


Figure 7-1 Detail of rotate_slitless.fits showing the overlap of object spectra.

7.3 Further Analysis

You could proceed as before to extract and calibrate these spectra, but you may not want to. A quick perusal of `rotate_slitless.fits` (reproduced in Figure 7-1) reveals that, because the objects in our simulation are now aligned with the dispersion axis of the spectrograph, their spectra (all five orders) overlap. Spectral overlaps occur on the real sky, of course, and aXe provides tools for tracking and flagging them, but these tools are better explored using a less toxic arrangement of sources.

It is possible to use drizzle routines to combine the horizontally- and vertically-dispersed spectra. Instructions for doing so are provided in *The WFC3 Cookbook*. Keep in mind that, for resolved objects like elliptical galaxies, the projection of the galaxy onto the dispersion axis – and thus the spectral resolution – of the horizontally- and vertically-dispersed spectra may differ significantly. You may find it better to model the two spectra separately, rather than combining them.

7.4 Reference Documents

[Kuntschner, H., Kümmel, M., Walsh, J. R., & Lee, J. C. 2012, The WFC3 IR Grism Data Reduction Cookbook, Version 1.15](#)